The pulsed light curves of Her X–1 as observed by BeppoSAX

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Abstract. We report on the timing analysis of the observation of the X–ray binary pulsar Her X–1 performed during the BeppoSAX Science Verification Phase. The observation covered more that two full orbital cycles near the maximum of the main–on in the 35 day cycle of Her X–1. We present the pulse profiles from 0.1 to 100 keV. Major changes are present below 1 keV, where the appearance of a broad peak is interpreted as re-processing from the inner part of the accretion disk, and above 10 keV, where the pulse profile is less structured and the main peak is appreciably harder. The hardness ratios show complex changes with pulse phase at different energies.

INTRODUCTION

Her X–1 is one of the most observed and best studied sources in the X–ray sky. This eclipsing binary pulsar (orbital period 1.7 days, pulsation period 1.23 sec) was one of the first X–ray sources in its class to be discovered [5,15]. It shows a 35 day period on–off cycle in which a main–on and a short–on are present. The flux from the source varies roughly a factor of three between the main-on and the short–on [6]. Low flux level emission was also detected between the two on of the 35 day cycle.

The pulsed light curves observed during main–on show a broad, structured single peak from 2 to 100 keV [14]. There is evidence that the pulse shape varies during the 35 day cycle both in the low energy band below 10 keV and in the hard X–rays above 20 keV. In 1–30 keV a double peaked pulse shape was observed with EXOSAT during the short–on state [16]. Soong et al. [14] measured with HEAO–1

a change in the 12–70 keV pulse shape during the main on, even if they conclude that the changes they observe are more likely related to the source intensity than to the phase of the 35 day cycle.

OBSERVATION

BeppoSAX is a program of the Italian Space Agency (ASI) with participation of the Netherlands Agency for Aerospace Programs (NIVR). It is composed by four co-aligned Narrow Field Instruments (NFIs) [1], operating in the energy ranges 0.1–10 keV (LECS) [13], 1–10 keV (MECS) [2], 3–120 keV (HPGSPC) [8] and 15–300 keV (PDS) [4]. Perpendicular to the NFI axis there are two Wide Field Cameras [7], with a $40^\circ \times 40^\circ$ field of view.

During the BeppoSAX Science Verification Phase (SVP) Her X–1 was observed from 1996 07 24 00:34:46 UT to 1996 07 27 11:54:46 UT. Data were telemetred in direct mode for all the four NFIs, with information on arrival time, energy and position for each photon. We report on the pulsed light curves observed during a fraction of the out–of–eclipse phase of the binary orbit.

The data were recorded in single–event mode: each detected photon was tagged with its arrival time in the detectors. The arrival times were corrected to the solar system barycentre and folded at the pulsar period of 1.2377396 s [11]. A correction for the Her X–1 orbital motion was also included.

RESULTS

The folded light curves as observed by BeppoSAX are shown in Figure 1. Two clear transitions are seen: one at approximately 1 keV and the other at approximately 10 keV.

The 1 keV transition goes from a broad sinusoidal pulse shape (Figure 1, panel (a)) to a more peaked pulse shape that remains almost unchanged up to 10 keV. The transition is accompanied by a phase shift of $\sim 250^\circ$.

The 10 keV transition goes from a structured single peak, with a prominent shoulder on its trailing edge, to an almost perfectly triangular pulse shape. The pedestal observed between phase 0.9 and phase 1.4 in Fig. 1 remains visible at least up to 40 keV. This second transition occurs exactly at the energy where the Her X–1 X–ray spectrum begins to deviate consistently from a simple power law shape [3].

These two transition are even more evident in Fig. 2, in which we show the ratios between light curves in different energy bands. The hardness ratios also show some complex changes in the 2–10 keV energy interval. These changes are percentually small, but are easily detected with high significance.

The transition at $\sim$1 keV is likely to be due to a change from a reflected to a directly observed pulse beam [9,11]. As discussed in [11], the phase shift of $\sim 250^o$

observed between the soft and the hard pulse shape suggests that the reflection zone is the inner part of a tilted accretion disk.

The pulse width decreases with energy above 2 keV, mainly due to the suppression at higher energies, above 10 keV, of the shoulder on the trailing edge of the peak. This variation of the pulse shape is likely due to a variation in the intrinsic beaming pattern with energy, as predicted by emission models (e.g. [10,17]). However it is not straightforward to obtain the observed asymmetric shapes directly from the models and from simple pencil or fan beams.

An attempt to introduce some degree of geometrical complexity in the emission region was done by Panchenko and Postnov [12], reproducing qualitatively the Her X–1 pulse shape. However our detailed and simultaneous measurement in a broad energy interval shows that any geometrically complex model must explain also the energy dependence of the pulse shapes. This can be done only by taking into account the spatial anisotropy and energy dependence of the intrinsic beaming pattern from the emission zone.

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REFERENCES

1. Boella G., Butler R.C., et al. 1997a, A&AS, 122, 299
2. Boella G., Chiappetti L., et al. 1997b, A&AS, 122, 327
3. Dal Fiume D., Orlandini M., et al. 1997, in preparation
4. Frontera F., Costa E., et al. 1997, A&AS, 122, 357
5. Giacconi R., Gursky H., et al. 1973, ApJ, 184, 227
6. Gorecki A., Levine A., et al. 1982, Apj, 256, 234
7. Jager R., Mels W.A., et al. 1997, A&AS, in press
8. Manzo G., Giarrusso S., et al. 1997, A&AS, 122, 341
9. McCray R.A., Shull J.M., Boynton P.E., et al., 1982, ApJ 262, 301
10. Mészáros P., Nagel W. 1985 ApJ, 299, 138.
11. Oosterbroek T., et al. 1997, A&A, in press
12. Panchenko I. E., Postnov K. A. 1994, A&A, 286, 497
13. Parmar A.N., Martin D.D.E., et al. 1997, A&AS, 122, 309
14. Soong Y., Gruber D.E., et al. 1990, ApJ, 348, 634
15. Tananbaum H., Gursky H., et al. 1972, Apj, 174, L143
16. Trümper J., Kahabka P., et al. 1986, ApJ, 300, L63
17. Yahel R. Z., 1980, A&A, 90, 26

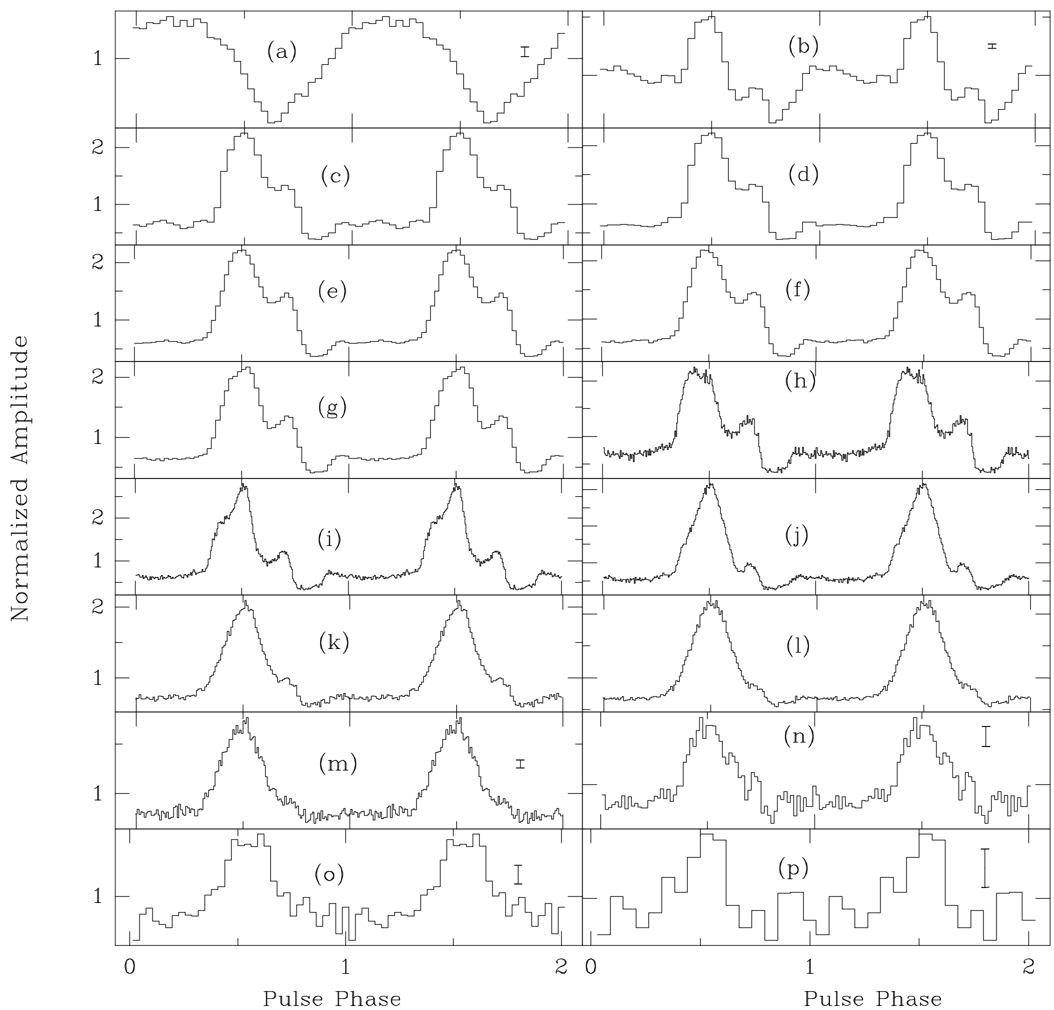

FIGURE 1.

Folded light curves of Her X-1: (a) 0.1–0.4 keV, LECS; (b) 0.4–1.6 keV, LECS; (c) 1.6–2.4 keV, LECS; (d) 2.4–10 keV, LECS; (e) 2–4 keV, MECS; (f) 4–6 keV, MECS; (g) 6–10 keV, MECS; (h) 4–8 keV, HPGSPC; (i) 8–15 keV, HPGSPC; (j) 15–30 keV, HPGSPC; (k) 13–20 keV, PDS; (l) 20–30 keV PDS; (m) 30–40 keV, PDS; (n) 40–50 keV, PDS; (o) 50–70 keV, PDS; (p) 70–100 keV, PDS. Where not indicated, the error bar is smaller than the symbol size.

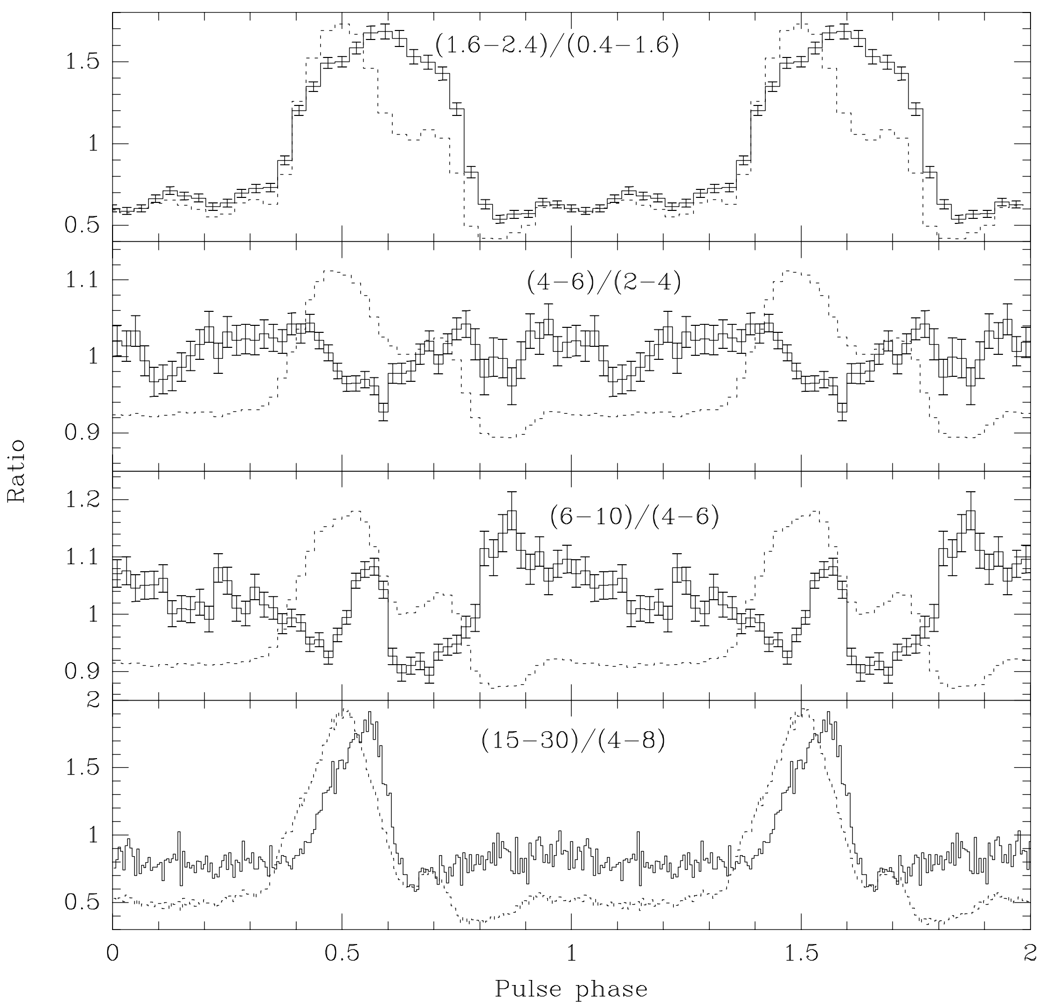

FIGURE 2.

Hardness ratios between folded light curves in different energy bands. In each panel the dashed line shows the measured light curve in the higher energy band for reference.